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Simultaneous control of ion flow energy and electron temperature in magnetized plasmas

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Ion flow energy along magnetic-field lines is precisely controlled by electrostatic acceleration in magnetized collisional and synthesized plasmas. The source is made up of an ion-production region and a plasma synthesis region; an electron emitter of mesh shape is installed between the regions and supplies the electrons to the synthesis region. The ion flow is generated by an electrostatic potential difference between these regions. Our experimental results demonstrate that only the ion flow energy can be controlled under constant electron density and temperature. Moreover, the electron temperature is also controllable and could be reduced to less than 0.5 eV. *© 2006 American Institute of Physics*. [DOI: 10.1063/1.2181653]

The ion energy and the electron temperature are key parameters in the field of plasma processing. In recent years, the production of pristine carbon nanotubes and the formation of atoms- or molecules-encapsulated carbon nanotubes have been significant research subjects for nanotechnological applications such as fabrication of nanoscale electronic devices. The effects of ion irradiation energy and flux to substrates on the nanotube growth in plasma enhanced chemical vapor deposition have been investigated, which were adjusted by the substrate bias voltage or the external magnetic-field strength.[1,2] When these external parameters are changed, however, the possibility arises that some plasma parameters, including ion species, will be unexpectedly varied. For this reason, there is need of a method for exclusively controlling the ion irradiation energy under constant experimental conditions, including constant ion species.

One of the solutions to the earlier-mentioned problems is to utilize ion beam sources, an example of which is the success of the nitrogen-ion doping of carbon nanotubes by low energy ion beams of about 30 eV.[3] However, the generation and control of low-energy ion beams of about 10–100 eV are difficult due to the space-charge limitation and only a few devices can realize it.[4,5] Another solution is to control the ion flow energy in plasmas. When a substrate is inserted into a plasma, the ion irradiation energy is given by the sum of the ion flow energy and the sheath voltage in front of the substrate. Therefore, it is expected that the ion irradiation energy can be controlled by the ion flow energy. Although the ion flow can easily be generated in double plasma devices, the ions have not only a beam component but also a bulk component in these machines.[6–8] For fundamental studies on the effects of the ion energy, it is favorable that the ions in plasmas have only a beam component and that their flow energies can be controlled under constant density, electron temperature, and so on. Although this has been realized only in *Q*-machine plasmas[9] so far, their ion species are limited to alkali metals and cannot be extended to other kinds of ion species, such as gaseous ones (helium, argon, and so on), which have played significant roles in various kinds of plasma applications.

In addition to the ion flow energy, the electron temperature is also important in plasma processing. A high electron temperature is considered to cause serious problems, such as substrate damage in the development of nanoscale materials and devices. Some plasma sources with low electron temperature have already been developed[10–12] and have gathered much attention.

As mentioned earlier, simultaneous control of the ion flow energy and the electron temperature is now required to be achieved in conjunction with the development of novel plasma sources. In this letter, we report control of the ion flow energy and the electron temperature by means of electrostatic acceleration in a plasma synthesis method.

Experiments are performed in the Q_T-Upgrade machine of Tohoku University as shown in Fig. 1, which has a cylindrical vacuum chamber of about 450 cm in length and 20.8 cm in diameter. Argon gas is introduced into the chamber and the operating gas pressure is 15 mPa. A uniform

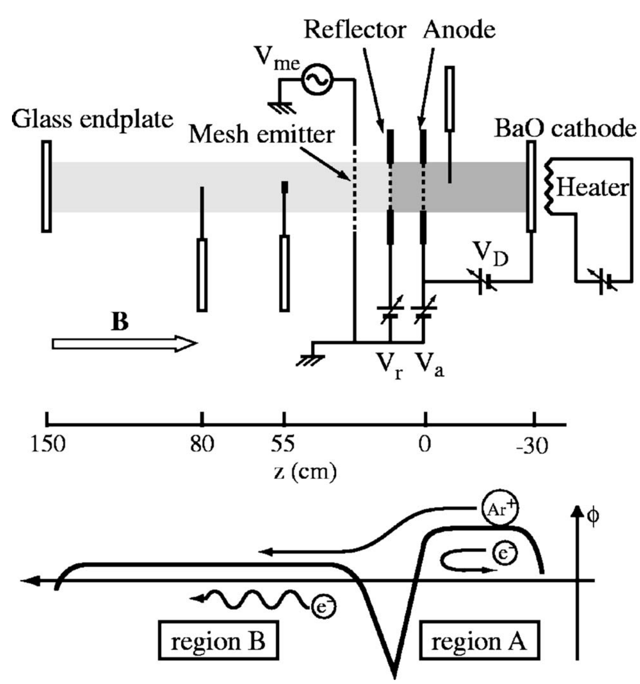

FIG. 1. Schematic diagram of the experimental setup and the model of the potential profile.

[a)]Electronic mail: kazunori@ecei.tohoku.ac.jp magnetic field can be applied by solenoidal coils and the operating magnetic-field strength is selected to be 1.6 kG. A barium oxide (BaO) cathode uniformly heated by a pyrolytic graphite-pyrolytic boron nitride heater and a tungsten mesh anode are set at the axial positions of $z=-30$ and 0 cm, respectively. A tungsten mesh reflector and an electron emitter of mesh shape, which is defined as a "mesh emitter," are located in front of the anode. The distances between the anode and the reflector, and between the reflector and the mesh emitter are 1 cm. The mesh emitter is constructed of the tungsten mesh covered with BaO for efficient electron emission at comparatively low temperature. The mesh emitter is heated by directly passing ac through the wires of the tungsten mesh and can emit electrons. The heating voltage V_{me} and current I_{me} for electron emission from the mesh emitter are about $V_{me}=4$ V and $I_{me}=30$ A, respectively.

A plasma is produced by a dc discharge between the BaO cathode and the anode for the production of argon ions, and this area is defined as "region A." The space potential in region A can be controlled by adjusting the anode potential V_a, and the reflector can be biased in the range of -120 V $< V_r < 0$ V. When the reflector is negatively biased enough to reflect the electrons from region A, only the ions produced in region A penetrate the reflector and go ahead several centimeters in obedience to the Child-Langmuir law. When the ions reach the mesh emitter, the ions and the electrons emitted from the mesh emitter are synthesized and flow downstream without the space-charge limitation. The synthesized plasma is terminated by a glass endplate located at $z=150$ cm. Here, we define the synthesis area between the mesh emitter and the glass endplate as "region B." The space potential in region B would be determined by the potential of the mesh emitter which supplies the electrons to region B. Then, the ion flow energy corresponding to the potential difference between regions A and B can be generated as presented at the bottom of Fig. 1. In addition, when all the electrons in region B are emitted from the mesh emitter, the electron temperature in the synthesized plasma would be reduced to that of thermionic electrons.

A Langmuir probe is inserted at $z=-5$ cm in order to measure plasma parameters in region A. The plasma parameters and an ion energy distribution function (IEDF) in region B can also be measured by the Langmuir probe and an electrostatic ion energy analyzer located at $z=80$ cm and $z=55$ cm, respectively.

Figure 2(a) shows a typical IEDF $-dI_c/dV_c$ parallel to the magnetic-field lines at the radial center of the plasma column and $z=55$ cm in region B, where I_c is the current flowing to a collector of the electrostatic ion energy analyzer and V_c is the collector voltage applied with respect to the ground. The solid arrow in Fig. 2(a) indicates the space potential ϕ_B measured at $z=80$ cm in region B. The IEDF clearly denotes the generation of ion flow along the magnetic-field lines, where the ion flow energy corresponds to the difference between the peak of the IEDF and ϕ_B. Here, the dissymmetric shape of the IEDF with respect to its maximum is considered to be caused by the collision of the ions with the neutral atoms and the resultant energy loss. The dependency of the IEDF in region B on V_a is presented in Fig. 2(b) as a contour plot together with the space potentials in region A (ϕ_A: open square) and region B (ϕ_B: open circle). Figure 2(b) presents that V_c yielding the peak of the IEDF is proportional to V_a and in good agreement with the space potential ϕ_A in region A. On the other hand, the space potential ϕ_B in region B is found to be independent of V_a and is determined by the potential of the mesh emitter supplying the electrons in region B. Thus, it is proved that the ion flow energy becomes large with an increase in V_a and can be precisely controlled simply by adjusting the space potential in region A, i.e., the anode potential V_a. In addition, we mention that the electron density and temperature in regions A and B are unchangeable when V_a is changed in the range of $V_a > 10$ V. As a result, it is possible to control only the ion flow energy under constant electron density and temperature. Under the conditions of Fig. 2, the electron density and temperature are $n_e \simeq 3\times10^{10}$ cm^{-3} and $T_e \simeq 3$ eV in region A, and $n_e \simeq 3\times10^{9}$ cm^{-3} and $T_e \simeq 0.4$ eV in region B, respectively.

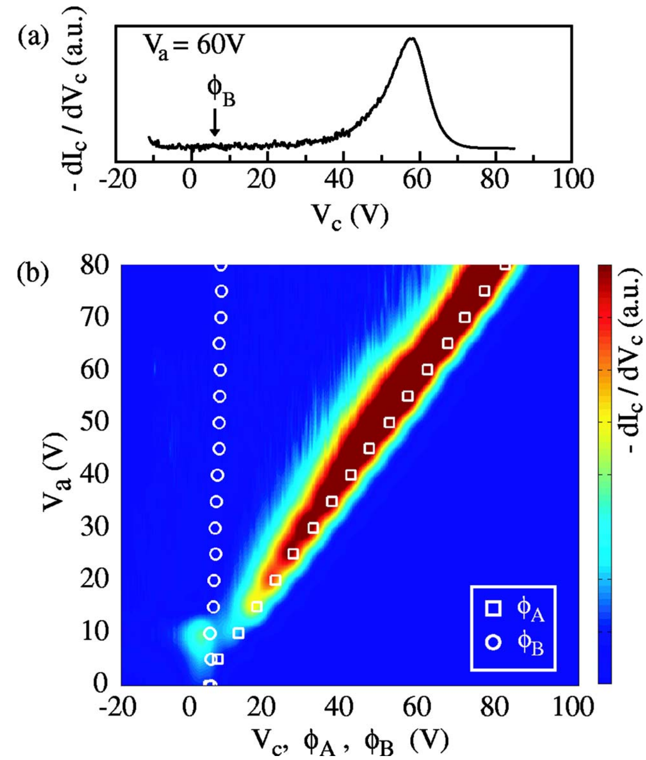

FIG. 2. (Color online) (a) Ion energy distribution function $-dI_c/dV_c$ (IEDF) parallel to the magnetic-field lines in region B for $V_a=60$ V. (b) Contour plot of the IEDF depending on V_a together with the space potentials in region A (ϕ_A: open square) and region B (ϕ_B: open circle).

Figure 3 shows the electron temperature T_e depending on the reflector potential V_r at $z=80$ cm in region B for $V_a=40$ V, which is deduced from current-voltage characteristics of the Langmuir probe by assuming a Maxwellian distribution. It is found that T_e for -20 V $< V_r < 0$ V is fairly high, which is considered to be caused by an inflow of the electrons from region A. In the range of -60 V $< V_r < -20$ V, T_e is found to be remarkably decreased but to be higher compared with that for $V_r < -60$ V. It is likely that only the high-energy-tail component of the electron energy distribution function in region A flows into and causes slight ionization in region B, though the bulk component is reflected at the potential barrier formed by the reflector. For the case of $V_r < -60$ V, since all the electrons from region A are reflected, the electrons in region B consist of only the thermionic electrons from the mesh emitter, which yields a low electron temperature ($T_e < 0.5$ eV). According to the result in Fig. 3, the electron temperature can be controlled to some

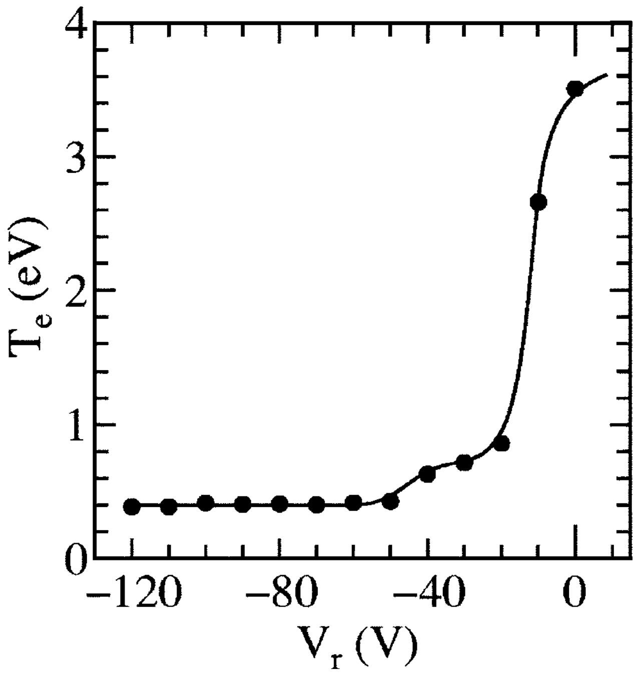

FIG. 3. Dependence of electron temperature T_e on reflector potential V_r, which is measured by the Langmuir probe located at $z=80$ cm in region B for $V_a=40$ V.

extent by adjusting the reflector potential, i.e., the quantity of the electron inflow from region A into region B.

In conclusion, the ion flow energy and the electron temperature are controlled for use in fundamental studies of plasma processing. The plasma source is made up of an ion-production region (region A) and a plasma-synthesis region (region B); the electrons in region B are supplied from the mesh emitter. Our results using the electrostatic ion energy analyzer evidence that ion flow energy of less than 100 eV can be controlled by adjusting only the space potential in region A under constant space potential in region B. Moreover, the electron temperature can also be controlled by the reflector potential and could be reduced to less than 0.5 eV, which is considered to correspond with the temperature of thermionic electrons emitted from the mesh emitter. Although the plasma in the ion-production region was produced by the dc discharge in our experiments, control of the ion flow energy and the electron temperature is believed to be realizable even if ions are generated by radio frequency, microwave, electron cyclotron resonance, or other discharges. Therefore, a plasma source suitable for the specifications, e.g., electron density, ion species, and so on, could be selected as that in the ion-production region. This plasma source could play an active part in fundamental studies of plasma processing in the near future.

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